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AIR WEATHER SERVICE

A METHOD FOR ESTIMATING MISSING HOURLY TEMPERATURES

USING DAILY MAXIMUM AND MINIMUM TEMPERATURES

by

WILLIAM R. SCHAUB, JR.

USAFETAC

Past Weather · Our Future

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PREFACE

This report documents the results of USAFETAC interbranch tasking 6075007, "Fill in of Hourly Temperatures for Long-Term Missing Data". It describes the development of a method for filling in missing hourly temperatures for locations that report only daily maximum and minimum temperatures. The analyst was Mr William R Schaub, Jr , USAFETAC/DNO.

The original support assistance request (USAFETAC Project 60750, "Request for Engineering Weather Data Support") was directed to USAFETAC/ECE from HQ USAF/LEEEU for the calculation of cooling degree hours (CDH). Since many locations that require CDH calculations have incomplete temperature records, ECE asked DNO to provide a way to "fill in" missing hourly temperatures.

This study is an extension of original work done by Maj W.F. Miller (1990). Miller developed a method for interpolating hourly temperatures when less than 6 consecutive hours of data are missing. The same temperature data was used in both studies.

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1. INTRODUCTION

1.1 Purpose of the Study. USAFETAC's Engineering Meteorology Section (USAFETAC/ECE) asked USAFETAC/DNO to develop a method for estimating missing hourly temperatures for locations that report only maximum and minimum temperatures, such as those in the NOAA Climatological Data (CD). USAFETAC/ECE required such a temperature estimation technique before they could calculate cooling degree hours (CDH) for stations at which only maximum and minimum temperatures were reported.

1.2 Previous Work. This study is an extension of work documented by USAFETAC/PR-90/006, *Short-Term Hourly Temperature Interpolation*, by Maj Walter F. Miller, December 1990. In his study, Miller described a method for interpolating hourly temperatures when less than 6 consecutive hours of data were missing. Input temperature data, the same for both studies, was taken from stations in different climates to test the temperature filling methods adequately. Those tests are described in Section 3. Test results and a description of the two computer programs developed for ECE are in Section 4.

2. TEMPERATURE DATA USED

2.1 Database. Hourly surface temperature data was obtained from DB2 tables. The data is stored in tenths of degrees F for worldwide military and civilian reporting stations. Typical period of record (POR) was from 1959 to 1988, with the exception of Scott AFB, which only had hourly temperature records from 1962 to 1985.

2.2 Test Stations. As USAFETAC/ECE recommended, the stations listed below were selected to test the temperature filling method, as shown, they are representative of continental, coastal, desert, subtropical, and tropical regions.

STATION	BLKSTN	LAT	LON	ELEV (Meters)	REGION
Scott AFB, IL	724338	38° 33'N	89° 33'W	138	Continental
Pease AFB, NH	726055	43° 05'N	70° 49'W	31	Continental/Coastal
McChord AFB, WA	742060	47° 09'N	22° 29'W	98	Subtropical
Luke AFB, AZ	722785	33° 32'N	112° 23'W	332	Desert
Homestead AFB, FL	722026	25° 29'N	90° 23'W	2	Subtropical/Coastal
Mildenhall AB, UK	035773	52° 22'N	0° 29'W	10	Continental
Ramstein AB, GE	106140	49° 26'N	7° 36'E	238	Continental
Honolulu, HI	911820	21° 21'N	157° 56'W	5	Tropical

PERIODS OF RECORD	
Scott AFB	Jan 1962 to Aug 1985
Pease AFB	Jan 1959 to Dec 1988
McChord AFB	Jan 1959 to Dec 1970; Jan 1973 to May 1988
Luke AFB	Jan 1958 to Dec 1970; Jan 1973 to May 1986
Homestead AFB	Jan 1959 to Dec 1970; Jan 1973 to Dec 1988
Mildenhall AB	Jan 1959 to Dec 1970; Jan 1973 to May 1988
Ramstein AB	Jan 1959 to Dec 1970; Jan 1973 to May 1988
Honolulu	Jan 1959 to Jun 1988

3. METHODOLOGY

3.1 Previous Models. The diurnal variation of temperature has been modeled previously in many ways Reicosky, et al., (1989) used random observations of hourly temperature data taken from over a period of 4 years Reicosky independently tested and evaluated five different methods that use daily maximum and minimum temperatures as input to generate temperatures for the missing hours and concluded that the best model was one developed by Hoogenboom and Huck (1986). The Hoogenboom/Huck model uses a cosine curve (with variable sunrise) connecting maximum and minimum temperatures to fit the diurnal temperature curve. The lowest root mean square error (RMSE) achieved by this model was 1.5 for one particular day when the diurnal trend was smooth throughout the 24-hour period.

3.2 The USAFETAC Model. In USAFETAC's study, the input temperature data described in Section 2 was used to evaluate three different methods for fitting a temperature curve given only maximum and minimum temperatures:

- simple cosine fit
- hyperbolic tangent fit
- cosine fit with variable sunrise

To test each method, the observed hourly temperatures were compared to values calculated by each method over a 24-hour interval. The results are discussed in Section 4.

3.3 Determination of Maximum and Minimum Temperatures. Maximum and minimum temperatures were determined for each station as follows: hourly temperature data for the station was obtained from USAFETAC's on-line relational database (DB2). Next, highest and lowest temperatures for each day were determined and stored in a separate dataset. The dataset with the daily maximum and minimum temperature was then used to model hourly temperature data as explained in the following paragraphs.

3.4 Simple Cosine Fit. In the first method, a simple cosine curve fitting algorithm is applied to the data As shown in Figure 1, the algorithm uses maximum and minimum temperatures (MAX1 and MIN1) for a given day and the minimum temperature (MIN2) for the next day.

In the simple cosine fit method, the minimum temperature is assumed to occur at 0500 local standard time (LST) and the maximum at 1400 LST. For convenience in calculations, the start time is set to zero. Therefore, the rise in temperature from 0500 to 1400 LST (hours 0 to 9) is described by the portion of the cosine function from A to B in Figure 1. The fall from 1400 to 0500 LST the next day (hours 10 to 23) is described by the portion of the cosine function from B to C.

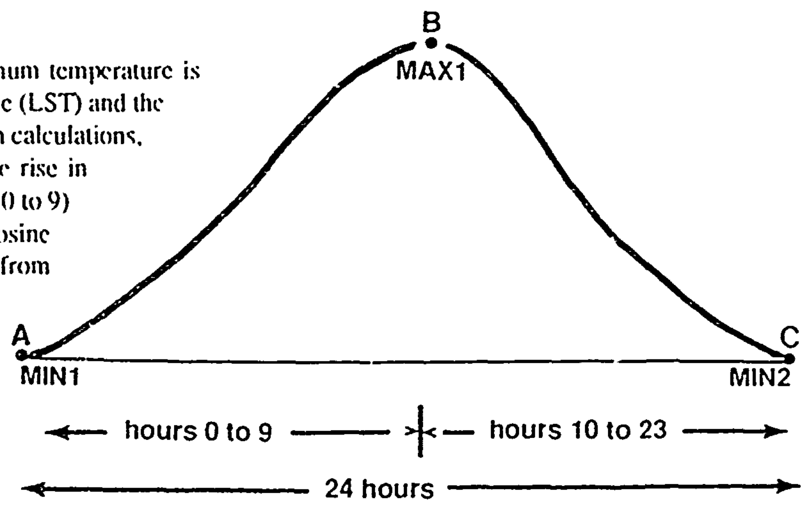

Figure 1. Illustration of simple cosine fit to maximum and minimum temperatures (MAX1 and MIN1) of one day and minimum temperature (MIN2) of the next day.

The simple cosine fit method fits a one-term cosine Fourier series to each half of the diurnal curve. To better understand this method as well as the one discussed in the next section, it is described in terms of a linear transformation. An independent variable (x) can be defined in terms of the time (hr) such that temperature becomes a linear function of x where

$$x = cos\left(hr \cdot \frac{\pi}{9}\right) \qquad (1)$$

for the hours (hr) from 0 to 9, and

$$x = cos\left[(hr - 10) \cdot \frac{\pi}{13}\right] \qquad (2)$$

for the hours from 10 to 23. Using the equation for a line,

$$y = mx + b \qquad (3)$$

where

y = dependent variable (temperature)
m = slope of the line
x = independent variable (a function of time)
b = ordinate (y - intercept),

and referring to Figure 1, the slope for segment AB is given by

$$-\left(\frac{MAX1 - MIN1}{2}\right)$$

and for segment BC by

$$\frac{MAX1 - MIN2}{2}$$

It was assumed that the y - intercept value for both segments was given by half the value of the amplitude or $\frac{MAX1 + MIN1}{2}$ and $\frac{MAX1 + MIN2}{2}$, respectively. By combining terms, the equations to calculate hourly temperatures for a day become

$$T(hr) = -\left(\frac{MAX1 - MIN1}{2}\right) \cdot cos\left(hr \cdot \frac{\pi}{9}\right) + \frac{MAX1 + MIN1}{2} \qquad (4)$$

where T (hr) is the hourly temperature for hours from 0 to 9, and

$$T(hr) = \left(\frac{MAX1 - MIN2}{2}\right) \cdot cos\left[(hr - 10) \cdot \frac{\pi}{13}\right] + \frac{MAX1 + MIN2}{2} \qquad (5)$$

where $T(hr)$ is the hourly temperature for hours from 10 to 23. After calculations were made, time was converted back to local standard time (LST) by adding 5 hours.

3.5 Hyperbolic Tangent Fit. In an attempt to improve curve fitting, the analyst tried the hyperbolic tangent function. The advantage of this function is that it approaches the maximum and minimum asymptotically so that plateaus, instead of peaks, are reached. Like the cosine, the maximum and minimum values are both 1. Using the same procedures to develop equations as in the cosine fit method, the temperature was transformed to a linear function of x, such that

$$x = tanh\left(\frac{hr - 4.5}{2.5}\right) \qquad (6)$$

for the hours from 0 to 9, and

$$x= tanh\left(\frac{hr - 16.5}{3.5}\right) \qquad (7)$$

for the hours from 10 to 23. Since the signs of the slopes are opposite those in the cosine fit, the total equation for the hours from 0 to 9 becomes

$$T\,(hr) = \frac{MAX1 - MIN1}{2} \cdot tanh\left(\frac{hr - 4.5}{2.5}\right) + \frac{MAX1 + MIN1}{2} \qquad (8)$$

and for the hours from 10 to 23,

$$T\,(hr) = -\frac{MAX1 - MIN2}{2} \cdot tanh\left(\frac{hr - 16.5}{3.5}\right) + \frac{MAX1 + MIN2}{2} \qquad (9)$$

Again, time is converted back to LST by adding 5 hours.

3.6 Cosine Fit with Variable Sunrise. In the temperature filling method that Reicosky, et. al. (1989), determined to be the best, sunrise was calculated to the nearest whole hour and that time was assigned to the minimum temperature. The maximum temperature was assumed to occur at 1400 LST. To determine if further temperature curve fitting improvements were possible in this study, the cosine fit method was used with sunrise (RISE) calculated to the nearest whole hour. Sunrise calculation is shown in the Appendix. The minimum temperature was assumed to occur at RISE, the maximum at 1400 LST. The linear transformation of temperature to a function of x was

$$x = cos\left[hr \cdot \frac{\pi}{(14 - RISE)}\right] \qquad (10)$$

for the hours from 0 to (14 - $RISE$), and

$$x = cos\left(\{hr - [(14 - RISE) + 1]\} \cdot \frac{\pi}{23 - (14 - RISE)}\right) \qquad (11)$$

for the hours from (14 - $RISE$) + 1 to 24. Hour 24 was calculated to account for when sunrise for tomorrow was an hour later than today. Any duplicate observations were removed when all temperatures had been calculated. The equations to calculate hourly temperatures for a day were

$$T = -\frac{MAX1 - MIN1}{2} \cdot x + \frac{MAX1 + MIN1}{2} \qquad (12)$$

for the hours from 0 to (14 - *RISE*) where x was obtained from Equation 10, and

$$T = \frac{MAX1 - MIN2}{2} \bullet x + \frac{MAX1 + MIN2}{2} \tag{13}$$

for the hours from (14 - *RISE*) + 1 to 24, where x was obtained from Equation 11.

4. TEST RESULTS AND PROGRAM.

4.1 Test Procedures. Each of the three temperature filling methods described in Section 3 were tested using daily temperatures for the stations listed in Section 2. The observed hourly temperatures were compared to the filled temperatures obtained from each method. To measure the accuracy of fit, the bias and RMSE were determined.

The bias, or mean of the error estimate, was determined from the following equation:

$$BIAS = \frac{\sum(T_o - T_f)}{N} \qquad (14)$$

where the difference between the observed hourly temperature (T_o) and the filled hourly temperature (T_f) is the error of estimate and N is the total number of observations. A positive bias indicates that on the average, the filled temperatures were lower than the observed, while a negative bias indicates filled temperatures were higher than the observed.

The RMSE was calculated from

$$RMSE = \sqrt{\frac{\sum(T_o - T_f)^2}{N-1}} \qquad (15)$$

The RMSE gives a measure of the size of the differences between the observed and filled temperature values. Since RMSE calculation is heavily influenced by a few large errors of estimate, RMSE may be larger than the error for most of the data points. To clarify this point, let's suppose a hypothetical day has an error of estimate of 1.0 for each hour except one, which has an error of estimate of 8.0. The calculated RMSE is about 2.0. One large difference between observed and filled temperature made the other 23 filled temperatures appear to be more in error than they actually were.

4.2 Results. The results of hourly temperature filling accuracy for all three methods are shown in Figure , units are degrees F.

Station	Cosine		Hyperbolic Tangent		Cosine with Sunrise	
	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE
Scott AFB, IL	-0.07	4.23	-0.07	4.20	-0.46	4.26
Pease AFB, NH	-0.15	4.14	-0.15	4.10	-0.50	4.13
McChord AFB, WA	-0.15	3.10	-0.15	3.06	-0.50	3.19
Luke AFB, AZ	0.05	3.48	0.06	3.45	-0.43	3.45
Homestead AFB, FL	-0.23	2.92	-0.23	2.90	-0.50	3.04
Mildenhall AB, UK	0.01	3.16	0.01	3.13	-0.27	3.16
Ramstein AB, GE	0.09	3.36	0.09	3.32	-0.26	3.34
Honolulu, HI	-0.66	2.16	-0.66	2.14	-0.92	2.26

Figure 2. Test results for three temperature filling methods. Units are ° F.

As shown by these results for all months and all hours, the hyperbolic tangent filling method was the best based on RMSE. It also proved best when only the typical summer period, from June to September, was used. This is shown in Figure 3.

Station	Cosine		Hyperbolic Tangent		Cosine with Sunrise	
	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE
Scott AFB, IL	-0.11	3.40	-0.11	3.40	-0.53	3.41
Pease AFB, NH	-0.26	3.61	-0.26	3.60	-0.63	3.63
McChord AFB, WA	-0.10	2.70	-0.10	2.60	-0.52	2.75
Luke AFB, AZ	0.58	3.48	0.58	3.42	0.04	3.45
Homestead AFB, FL	-0.30	3.00	-0.30	2.97	-0.53	3.08
Mildenhall AB, UK	-0.01	2.97	-0.01	2.94	-0.36	2.81
Ramstein AB, GE	0.14	3.10	0.14	3.06	-0.30	3.07
Honolulu, HI	-0.84	2.06	-0.84	2.05	-1.07	2.23

Figure 3. Same as Figure 2, except for summer months from June to September. Units are ° F.

4.3 Median RMSE and Absolute Extreme Difference. Another way to evaluate accuracy of fit is to examine the median (50th percentile) RMSE and absolute extreme difference. These two statistics are shown in Figure 4 for each temperature filling method, for each station.

Station	Cosine		Hyperbolic Tangent		Cosine with Sunrise	
	Median	Abs Ext	Median	Abs Ext	Median	Abs Ext
Scott AFB, IL	1.81	39.70	1.65	38.76	1.81	39.70
Pease AFB, NH	1.90	38.70	1.76	37.67	1.90	38.70
McChord AFB, WA	1.62	22.13	1.51	22.28	1.65	20.41
Luke AFB, AZ	2.01	25.15	1.99	25.97	1.90	26.46
Homestead AFB, FL	1.59	23.34	1.50	22.57	1.67	23.10
Mildenhall AB, UK	1.68	22.69	1.51	22.06	1.68	23.24
Ramstein AB, GE	1.73	32.40	1.55	31.67	1.69	33.94
Honolulu, HI	1.23	19.45	1.17	19.67	1.25	20.00

Figure 4. Median RMSE and absolute extreme difference (Abs Ext) for three temperature filling methods. Periods of record are as in Figure 2. Units are ° F.

As before, the hyperbolic tangent method achieved the lowest RMSE. The median RMSE values for each station show that at the 50th percentile level, the RMSE ranged from 1.17° F in the tropics to 1.99° F in the mid latitudes. At the extreme end, errors in excess of an order of magnitude greater than the median contributed to raising the overall RMSE, as explained earlier. Many of the extreme errors are caused by frontal passages. An example is shown in Figure 5, where the 24-hour period containing the extreme for the hyperbolic tangent method for Scott AFB is used to plot the filled and observed hourly temperatures for each hour. The extreme error occurred at 1500 LST on 28 January 1977.

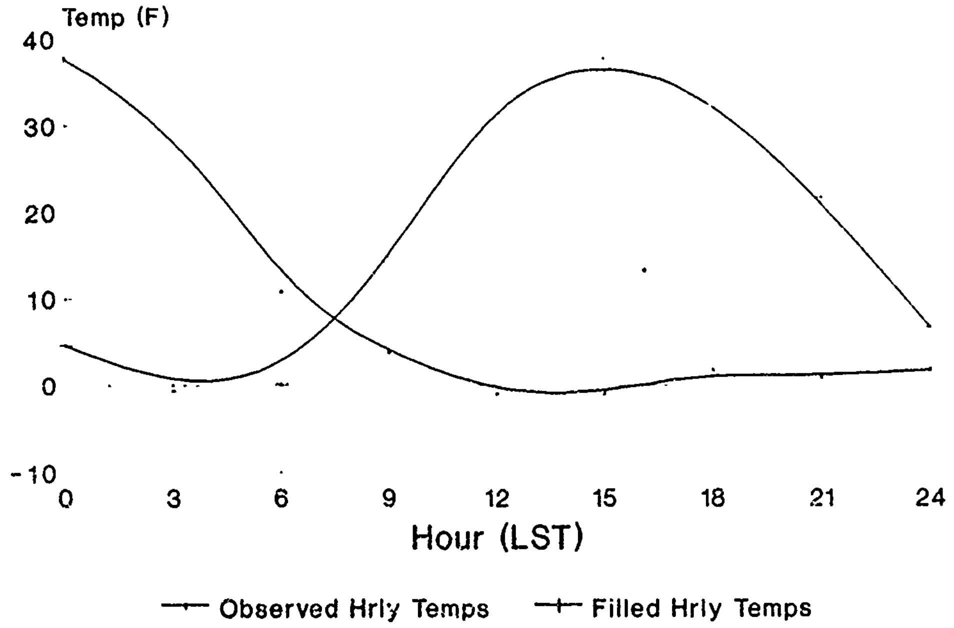

Figure 5. Plots of filled hourly temperatures and observed hourly temperatures for Scott AFB, 28 January 1977.

In this example, the maximum temperature for the day actually occurred at midnight and resulted in large errors of estimate (observed minus filled temperature values) for that day. Without additional information, a computer program cannot account for these anomalous cases. The effects of days like the one illustrated are more pronounced during seasons (and at locations) with frequent frontal passages, but they are minimized over long periods of record. An additional source of variance will occur when this method is applied to the NOAA Climatological Data. As explained by McFarland, Miller, and Neale (1990), the reported minimum temperature often relates to the previous day's minimum when the observation time is 0500 LST.

4.4 The Programs. Based on the favorable test results for the hyperbolic tangent temperature filling method, Equations 8 and 9 were used as algorithms to write a Statistical Analysis System (SAS) program for use by USAFETAC/ECE (SAS is the registered trademark of SAS Industries, Inc, Cary, NC). The program (MXMNFILL) calculates values for missing hourly temperatures given input of daily maximum and minimum temperatures. To account for locations that close on weekends and holidays, another program (WEEKEND) was developed to linearly interpolate daily maximum and minimum temperatures when less than 3 consecutive days were missing. For the test results shown in Figure 2, every 6th and 7th day's maximum and minimum temperatures were set to missing. When WEEKEND was used to replace the temperatures, RMSE was raised by 1° F for the mid-latitudes and subtropics, but only slightly for the tropics.

5. SUMMARY.

5.1 Temperature Filling Method. This report describes the development and testing of a method for filling in missing hourly temperatures at locations where only maximum and minimum daily temperatures are reported. The method uses the hyperbolic tangent function with the temperature transformed to a linear function of the hour. The advantage in using the hyperbolic tangent is that temperatures near the maximum and minimum are allowed to approach those points gradually.

5.2 Accuracy. Tests of the method, using hourly temperature data for all months and all hours for eight locations in different climatic regions, showed an RMSE from 2° F for the tropics to 4° F for mid-latitudes. Using the same data for the typical summer period (June to September, when frontal passage is less frequent), RMSE values were about 10 percent lower. If this method is applied to stations that only report maximum and minimum temperatures, accuracy will decrease further due to variances associated with this type of reporting station.

5.3 The Programs. USAFETAC/DNO used the hourly temperature algorithms developed for the hyperbolic tangent temperature filling method to write two SAS programs for USAFETAC/ECE. One program (MXMNFILL) generates a dataset of estimated hourly temperatures given input of daily maximum and minimum temperatures. The other (WEEKEND) accounts for locations that may not be open 7 days a week by providing interpolated daily maximum and minimum temperatures for cases in which the data gaps are less than 3 days.

APPENDIX

Sunrise Calculations

The sun's declination angle, DECLIN, is obtained from Cox (1987):

$$DECLIN = -23.45 \cos \left[(JULSEC + 777{,}600)\,(YRTORAD) \right]$$

where JULSEC is the number of seconds from 1 January 1960 and 777,600 is the number of seconds from the winter solstice to 1 January: $YRTORAD = \frac{2\pi}{365.25 \cdot 24 \cdot 3{,}600}$ and takes into account the fact that the earth revolves around the sun (2π) in 1 year. The solar zenith angle (Z) can be calculated from:

$$\cos(Z) = \sin(LAT)\,\sin(DECLIN) + \cos(LAT)\,\cos(DECLIN)\,\cos(HRANG)$$

where LAT is the latitude of the site, and HRANG is the hour angle of the sun. At sunrise, the zenith angle is -90° or cos(Z) = 0. Solving the above equation for HRANG yields

$$COSHRANG = -(TANDEC \cdot TANLAT)$$

where the tangent of the declination angle,

$$TANDEC = TAN\left(DECLIN \cdot \frac{\pi}{180}\right)$$

and the tangent of the latitude in decimal form (LATDEC) is given by

$$TANLAT = TAN\left(LATDEC \cdot \frac{\pi}{180}\right)$$

When COSHRANG is greater than -1 and less than or equal to 1, the sun would never rise. For our purposes however, we assume sunrise is at noon so that a sunrise to the 1400 LST portion of the curve can be calculated

$$HRANG = ARCOS\,(COSHRANG)$$

Otherwise, $HRANG = 0$. The sunrise in local time is then obtained from

$$RISE = 12 - \frac{HRANG}{\left(\frac{\pi}{180} \cdot 15\right)}$$

where the sun is vertical at 1200 LST and 1 hour of time is equivalent to 15° longitude.

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GLOSSARY

Abs Ext	absolute extreme difference
CDH	cooling degree hours
DB2	USAFETAC's on-line relational database
DNO	the Operations Applications Development Section of USAFETAC's Aerospace Sciences Branch
ECE	the Engineering Meteorology Section of USAFETAC's Environmental Applications Branch
F	Fahrenheit
hr	hour
LST	local standard time
MAX1	maximum temperature of 1 day
MIN1	minimum temperature of 1 day
MIN2	minimum temperature of the next day
POR	period of record
RISE	sunrise
RMSE	root mean square error

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